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DESIGN STUDY OF WIND TURBINES 50 kW TO 3000 kW FOR ELECTRIC UTILITY APPLICATIONS

VOLUME III - SUPPLEMENTARY DESIGN AND ANALYSIS TASKS

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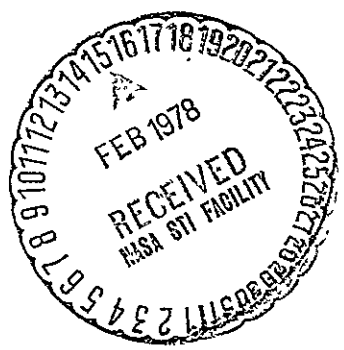

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Division of Solar Energy
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16 Abstract

This study was conducted to provide additional design and analysis data to supplement the results of the two parallel design study efforts. The key results of the three supplemental tasks investigated are:

- The velocity duration profile has a significant effect in determining the optimum wind turbine design parameters and the energy generation cost.
- Modest increases in capacity factor can be achieved with small increases in energy generation costs and capital costs.
- Reinforced concrete towers that are esthetically attractive can be designed and built at a cost comparable to those for steel truss towers.

The approach used, method of analysis, assumptions made, design requirements, and the results for each task are discussed in detail in this report.

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SECTION 1

INTRODUCTION

As part of the wind turbine generator design study performed under contract NAS 3-19403, reference designs were defined for 500 kW and 1500 kW systems intended for electric utility application. During the study, many questions were raised that indicated a need for further study. Subsequent to the principal design study three supplemental design and analysis tasks were pursued and are the subject of this report. The objectives of these tasks were:

- To determine the effect on the design of wind turbine generators of variations in the velocity duration profile for sites having the same mean wind speed.
- To determine the sensitivity of energy generation costs to the capacity factor of wind turbine generators.
- To determine the cost of an esthetically designed, reinforced concrete tower for a wind turbine generator.

The results of the three supplemental tasks are presented in subsequent sections of this report. The conclusions reached as the result of these studies are summarized at the end of each section.

SECTION 2

DESIGN SENSITIVITY TO VELOCITY DURATION PROFILE

2.1 INTRODUCTION

Potential sites for wind turbine generators at various geographical locations that are characterized by the same mean wind speed will not have identical velocity duration profiles. It is the objective of this task to determine the effect of variations in the velocity duration profile on the design of wind turbine generators. The sensitivity to variations in the velocity duration profile will indicate whether mean wind speed is an adequate parameter to characterize potential installation sites. Further, the sensitivity of performance characteristics to variations in the velocity duration profile will be an indication of the cost penalties associated with placing an existing WTG design in different locations having the same mean wind speed.

The approach will be to optimize the design for wind turbine generators with assumed variations in the velocity duration profile provided by NASA-LeRC, and compare their costs with those calculated for the baseline designs defined in the previous design study (Reference 1). For each extreme value of the velocity duration profile, cost comparisons will be made both for energy generation costs (¢/kWh) and capital investment costs ($/kW). To determine the cost penalty associated with operating a WTG in a velocity duration profile other than the one for which it was designed, the performance of the baseline designs will be analyzed for assumed extremes in the velocity duration profile. The cost differences for these extremes as compared with nominal design conditions will be an indication of the cost penalty incurred.

2.2 METHOD OF ANALYSIS

The design points used as a baseline in this task are those that were derived for 500 kW and 1500 kW systems as part of the design study reported in Reference 1. The system parameters of these baseline designs are provided for reference in Table 2-1. These designs were optimized for minimum energy generation cost assuming velocity profiles having median speeds of 5.36 m/s (12 mph) and 8.05 m/s (18 mph), respectively. The computer program used for this analysis is one which was used as a model to calculate system costs and energy production of a WTG system, coupled with a method-of-steepest-ascent optimization code. The independent variables selected for optimization were rated power (Pr), velocity ratio at rated power (λr), and rotor speed (Nr). The capacity factor (CF), of the WTG system was a dependent variable in this analysis, but was examined separately in an analysis that will be discussed in Section 3 of this report. In Table 2-2 are listed some of the significant assumptions and design factors that were held constant throughout the current study.

Variations in the velocity duration profile were defined by the Weibull function:

$$P = e^{-(v/c)^k}$$

where P = probability of velocity of v or greater

v = wind speed

c = Weibull parameter related to mean wind speed

and k = Weibull parameter related to the shape of the curve.

note: v and c must have same units of velocity

TABLE 2-1

SYSTEM PARAMETERS OF BASELINE PRELIMINARY DESIGN

SYSTEM PARAMETERS	500 kW 5.36 m/s (12 mph) median wind	1500 kW 8.05 m/s (18 mph) median wind
Rated velocity ratio*	8.87	9.37
Rated rotor speed (rpm)	28.82	40.77
Rotor diameter (m)	55.58	57.83
Rated wind velocity (m/s)	7.30	10.13
Cut-in wind velocity (m/s)	3.52	5.10
Annual energy (10^6 kWh)	1.88	6.61
Rotor thrust (kN)	88.13	193.6
Generator torque (kN-m)	2.83	8.40
Rotor torque (kN-m)	184.2	386.6
Cut-out wind velocity (m/s)	15.57	22.48
Energy generation cost (¢/kWh)	3.10	1.32
Capital investment cost ($/kW)	712	354

* Rated velocity ratio = $\frac{\text{rotor blade tip speed}}{\text{rated wind speed}}$

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TABLE 2-2

ASSUMPTIONS AND DESIGN FACTORS

ROTOR	23000 SERIES AIRFOIL ACTIVITY FACTOR = 30 OPTIMIZED TAPER AND TWIST
WIND	DURATION CURVES REFERENCED TO 9.144 m (30 FT) BLADE GROUND CLEARANCE = 15.24 m (50 FT) TERRAIN FACTOR = .167 AIR DENSITY (AT 50m) = 1.219 kg/m^3 (.002365 SLUGS/FT^3)
ECONOMICS	COMPONENTS MANUFACTURED AT RATE OF 100/YR. DEBT FRACTION = .5 EQUITY FRACTION = .5 DEBT INTEREST = .09 EQUITY INTEREST = .115 CORPORATE INCOME TAX = .48
GENERATOR	CONSTANT SPEED

For sites having a mean wind speed of 5.36 m/s (12 mph), the assumed parameters for extreme cases of wind duration profile were:

(a) c = 6.05 m/s (13.53 mph), k = 1.6

(b) c = 6.05 m/s (13.53 mph), k = 2.4

For sites having a mean wind speed of 8.05 m/s (18 mph), the assumed parameters for extreme cases of wind duration profile were:

(a) c = 9.1 m/s (20.36 mph), k = 2.1

(b) c = 9.1 m/s (20.36 mph), k = 2.8

These distributions are shown in Figures 2-1 and 2-2, compared with the velocity duration profiles used in deriving the baseline design points. Note that the profiles used in the baseline design study were defined for median wind speeds, and equate to mean wind speeds of approximately 5.36 m/s (12 mph) and 8.27 m/s (18.5 mph) for the two profiles used.

Median in statistics refers to the mid-point of a distribution. The median velocity is thus that value which is exceeded one half of the time and not reached the other half. It is easily found by entering the velocity duration curve at 4380 hours (8760/2) and reading median velocity directly. The mean velocity, on the other hand, is the numerical average of all velocities and is a more statistically meaningful parameter.

For each of the velocity duration profiles defined by the Weibull function, otpimized designs were calculated for rated powers of 500, 1000, 1500, and 2000 kW, using minimum energy generation cost as the payoff function. The results are summarized in Figures 2-3 and 2-4, and in Tables 2-3 through 2-6. Using the design parameters for the baseline WTG system at 500 kW and 1500 kW, the energy produced was calculated for each velocity duration profile; the 500 kW unit operating at a mean wind speed of 5.36 m/s (12 mph), and the 1500 kW unit operating at a mean wind speed of 8.05 m/s (18 mph). These results are summarized in Tables 2-7 and 2-8.

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FIGURE 2-1
VELOCITY DURATION CURVE
12 M. P. H. MEAN WIND SPEED

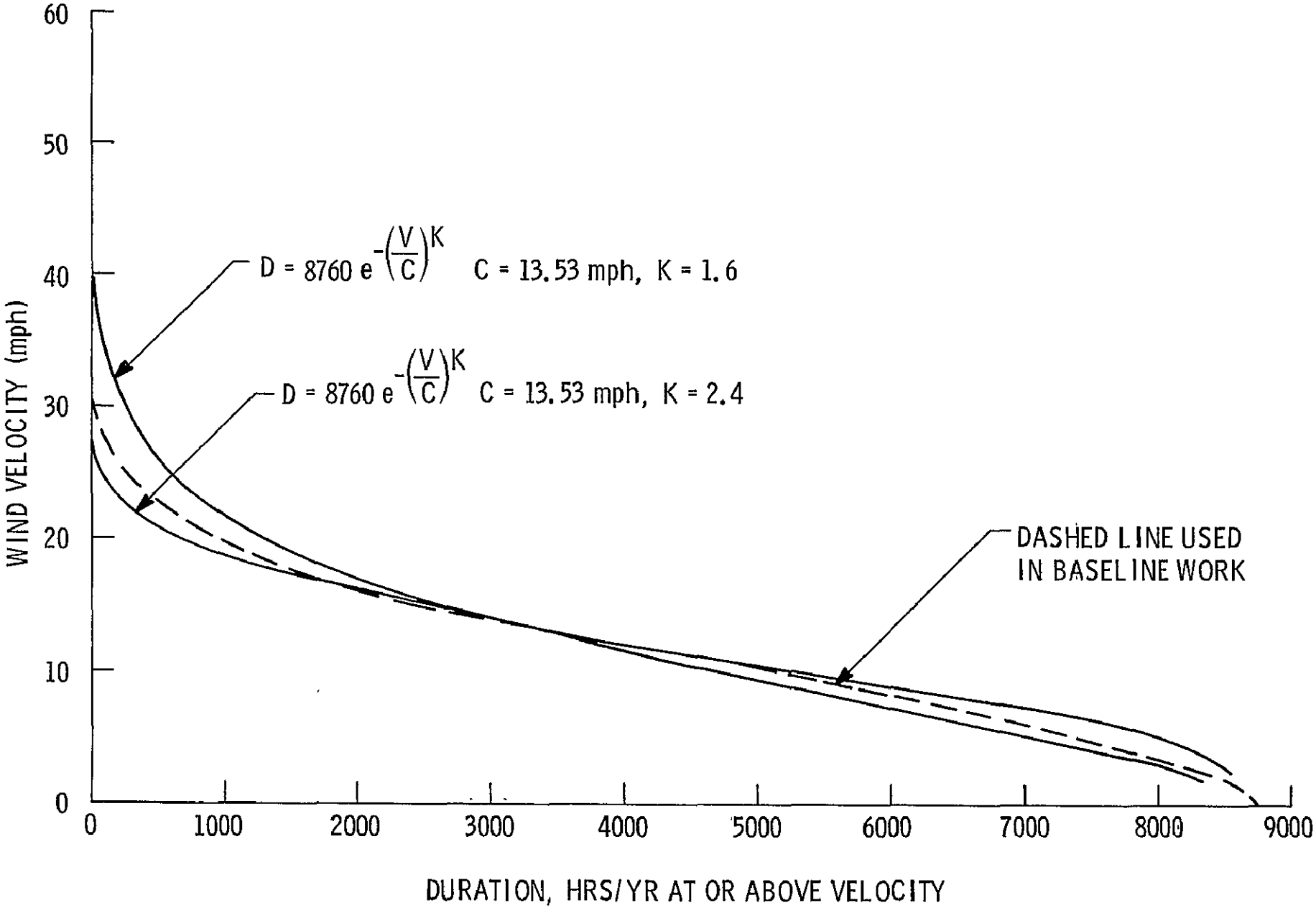

FIGURE 2-2
VELOCITY DURATION CURVE
18 M.P.H. MEAN WIND SPEED

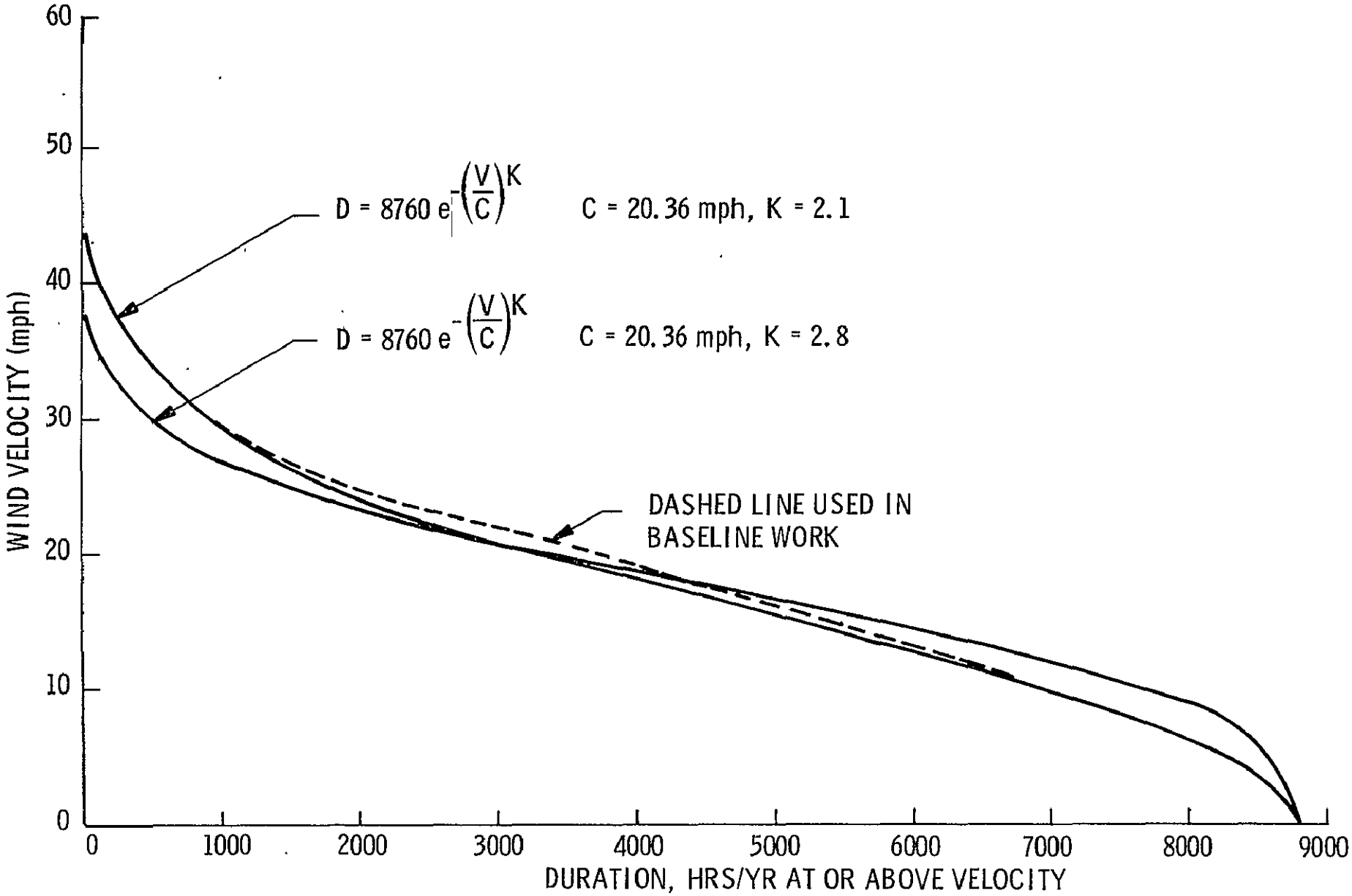

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FIGURE 2-3

ENERGY GENERATION COSTS
FOR
OPTIMIZED WTG SYSTEMS

MEAN WIND SPEED = 5.36 m/s (12 MPH)

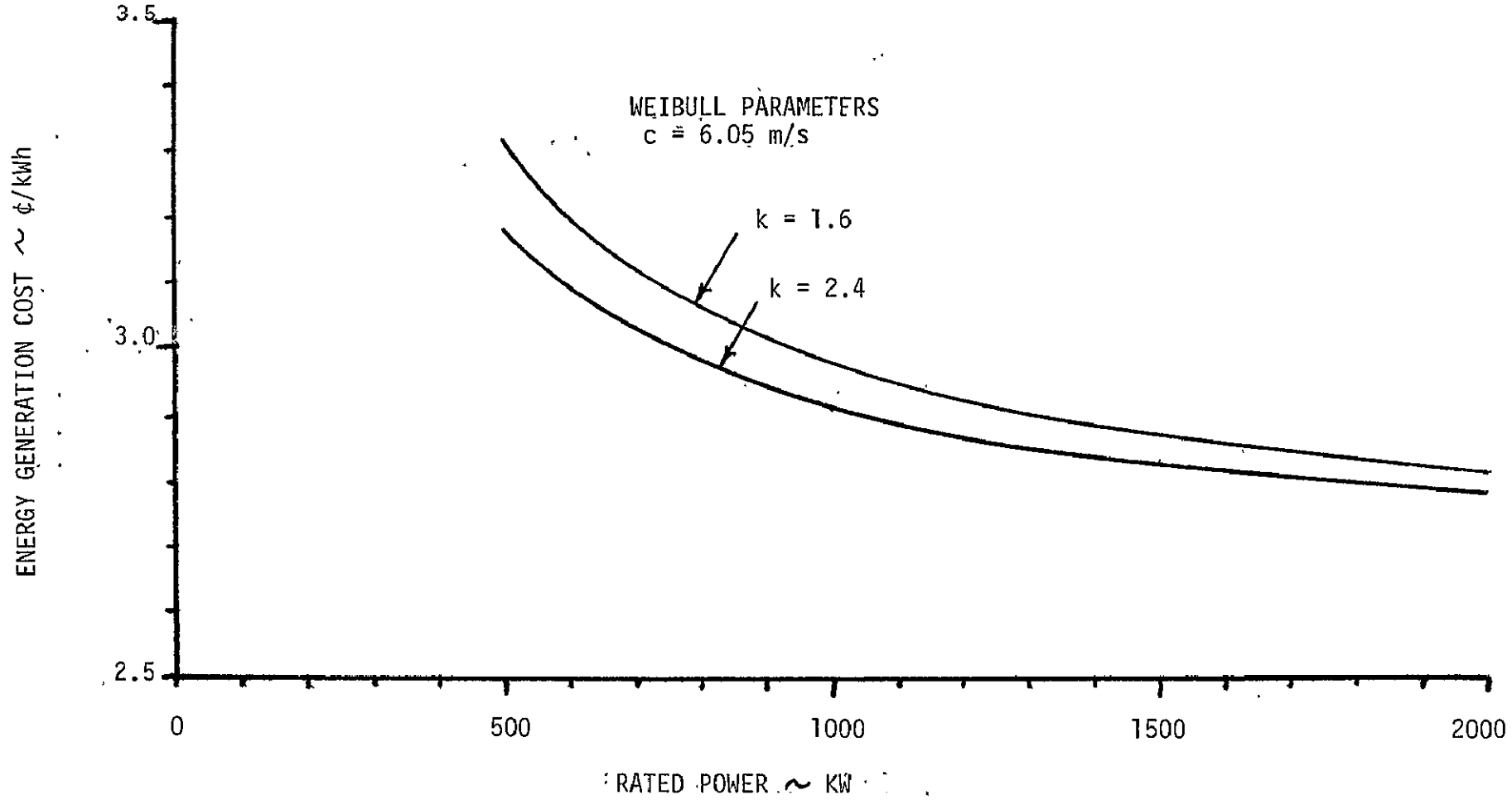

FIGURE 2-4

ENERGY GENERATION COSTS
FOR
OPTIMIZED WTG SYSTEMS

MEAN WIND SPEED = 8.05 m/s (18 MPH)

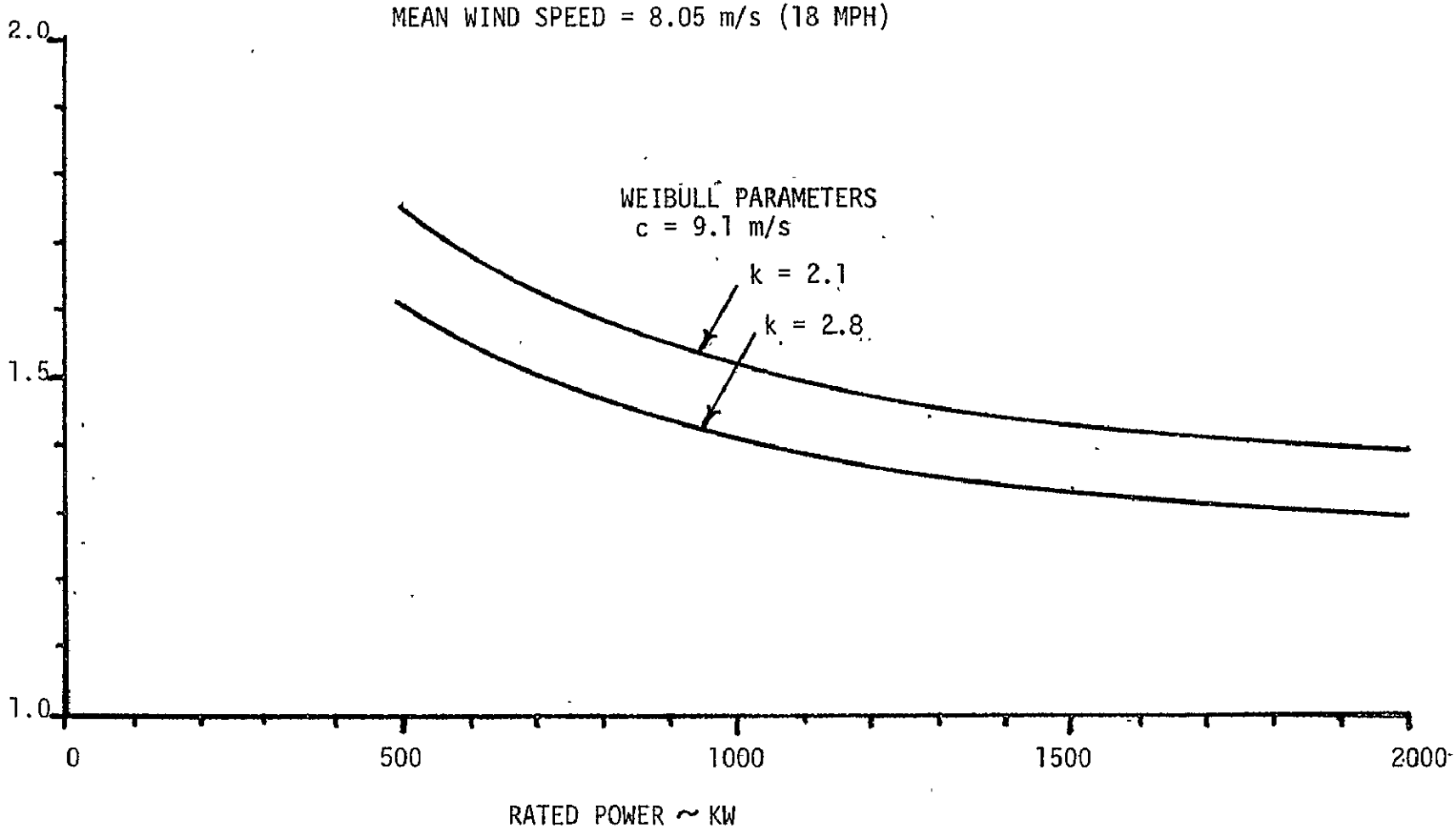

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TABLE 2-3

OPTIMUM WTG DESIGN PARAMETERS

MEAN WIND SPEED 5.36 m/s (12 MPH)

WEIBULL PARAMETERS c = 6.05 m/s, k = 1.6

RATED POWER (kW)	500	1000	1500	2000
RATED VELOCITY RATIO*	8.84	9.33	9.37	9.17
RATED ROTOR SPEED (rpm)	33.72	30.39	26.21	24.76
ROTOR DIAMETER (m)	50.48	63.52	75.42	81.51
RATED WIND VELOCITY (m/s)	7.87	8.24	8.23	8.52
CUT-IN WIND VELOCITY (m/s)	3.78	4.13	4.14	4.22
CUT-OUT WIND VELOCITY (m/s)	16.73	18.29	18.28	18.53
ANNUAL ENERGY (10^6 kWh)	1.56	2.84	4.27	5.41
ROTOR THRUST (kN)	82.46	157.4	231.2	289.4
GENERATOR TORQUE (kN-m)	2.83	5.63	8.40	11.14
ROTOR TORQUE (kN-m)	157.4	347.5	601.4	844.5
ENERGY GENERATION COST (¢/kWh)	3.32	2.98	2.87	2.81
CAPITAL INVESTMENT COST ($/kW)	628	518	501	467

* Rated velocity ratio = $\frac{\text{rotor blade tip speed}}{\text{rated wind speed}}$

TABLE 2-4

OPTIMUM WTG DESIGN PARAMETERS

MEAN WIND SPEED 5.36 m/s (12 MPH)

WEIBULL PARAMETERS c = 6.05 m/s, k = 2.4

RATED POWER (kW)	500	1000	1500	2000
RATED VELOCITY RATIO*	8.88	9.45	9.54	9.61
RATED ROTOR SPEED (rpm)	26.68	22.49	20.18	18.85
ROTOR DIAMETER (m)	58.22	76.65	89.09	98.66
RATED WIND VELOCITY (m/s)	7.04	7.11	7.21	7.31
CUT-IN WIND VELOCITY (m/s)	3.39	3.60	3.68	3.76
CUT-OUT WIND VELOCITY (m/s)	15.02	15.93	16.23	16.50
ANNUAL ENERGY (10^6 kWh)	1.95	3.77	5.50	7.14
ROTOR THRUST (kN)	90.91	179.9	261.4	539.6
GENERATOR TORQUE (kN-m)	2.83	5.63	8.40	11.15
ROTOR TORQUE (kN-m)	198.9	469.7	781.2	1109.3
ENERGY GENERATION COST (¢/kWh)	3.18	2.91	2.83	2.78
CAPITAL INVESTMENT COST ($/kW)	760	677	640	616

* Rated velocity ratio = $\frac{\text{rotor blade tip speed}}{\text{rated wind speed}}$

TABLE 2-5

OPTIMUM WTG DESIGN PARAMETERS

MEAN WIND SPEED 8.05 m/s (18 MPH)

WEIBULL PARAMETERS c = 9.1 m/s, k = 2.1

RATED POWER (kW)	500	1000	1500	2000
RATED VELOCITY RATIO*	9.14	9.43	9.41	9.46
RATED ROTOR SPEED (rpm)	51.16	43.35	40.27	36.50
ROTOR DIAMETER (m)	40.03	51.63	58.39	65.74
RATED WIND VELOCITY (m/s)	9.36	9.68	10.05	10.07
CUT-IN WIND VELOCITY (m/s)	4.62	4.89	5.07	5.11
CUT-OUT WIND VELOCITY (m/s)	20.44	21.64	22.38	22.44
ANNUAL ENERGY (10^6 kWh)	2.26	4.30	6.12	8.13
ROTOR THRUST (kN)	72.10	138.0	195.3	256.2
GENERATOR TORQUE (kN-m)	2.83	5.63	8.40	11.15
ROTOR TORQUE (kN-m)	103.7	243.6	391.4	572.8
ENERGY GENERATION COST (¢/kWh)	1.76	1.52	1.44	1.40
CAPITAL INVESTMENT COST ($/kW)	479	398	358	348

* Rated velocity ratio = $\frac{\text{rotor blade tip speed}}{\text{rated wind speed}}$

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TABLE 2-6

OPTIMUM WTG DESIGN PARAMETERS

MEAN WIND SPEED 8.05 m/s (18 MPH)

WEIBULL PARAMETERS c = 9.1 m/s, k = 2.8

RATED POWER (kW)	500	1000	1500	2000
RATED VELOCITY RATIO*	9.25	9.31	9.64	9.54
RATED ROTOR SPEED (rpm)	47.32	40.55	36.67	33.29
ROTOR DIAMETER (m)	42.25	53.37	62.63	69.83
RATED WIND VELOCITY (m/s)	8.98	9.44	9.51	9.60
CUT-IN WIND VELOCITY (m/s)	4.47	4.72	4.89	4.90
CUT-OUT WIND VELOCITY (m/s)	19.79	20.90	21.58	21.54
ANNUAL ENERGY (10^6 kWh)	2.60	4.85	7.15	9.42
ROTOR THRUST (kN)	75.37	139.9	208.2	268.4
GENERATOR TORQUE (kN-m)	2.83	5.63	8.40	11.15
ROTOR TORQUE (kN-m)	112.2	200.5	429.8	628.1
ENERGY GENERATION COST (¢/kWh)	1.61	1.41	1.34	1.30
CAPITAL INVESTMENT COST ($/kW)	506	415	388	376

*. Rated velocity ratio = $\frac{\text{rotor blade tip speed}}{\text{rated wind speed}}$

TABLE 2-7

BASELINE 500 kW WTG OPERATING IN VARYING WIND PROFILES

PARAMETER	PRELIMINARY DESIGN WIND DISTRIBUTION	WEIBULL PARAMETERS c = 6.05 m/s, k = 1.6	WEIBULL PARAMETERS c = 6.05 m/s, k = 2.4
MEAN WIND SPEED m/s (MPH)	5.36(12)	5.36 (12)	5.36 (12)
ANNUAL ENERGY (10^6 kWh)	1.88	1.74	1.83
CAPACITY FACTOR	.43	.40	.42
ENERGY GENERATION COST (¢/kWh)	3.10	3.36	3.19
CAPITAL INVESTMENT COST ($/kW)	712	712	712

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TABLE 2-8

BASELINE 1500 kW WTG OPERATING IN VARYING WIND PROFILES

PARAMETER	PRELIMINARY DESIGN WIND DISTRIBUTION	WEIBULL PARAMETERS c = 9.1 m/s, k = 2.1	WEIBULL PARAMETERS c = 9.1 m/s, k - 2.8
MEAN WIND SPEED m/s (MPH)	8.27 (18.5)	8.05 (18)	8.05 (18)
ANNUAL ENERGY (10^6 kWh)	6.61	6.05	6.48
CAPACITY FACTOR	.50	.46	.49
ENERGY GENERATION COST (¢/kWh)	1.32	1.44	1.35
CAPITAL INVESTMENT COST ($/kW)	354	354	354

2.3 DISCUSSION OF RESULTS

2.3.1 DESIGNS OPTIMIZED FOR VELOCITY PROFILE

The energy generation costs (¢/kWh) calculated for systems optimized at the extremes in velocity duration profile, as shown in Tables 2-3 through 2-6, were in all cases higher than those calculated for the baseline design points. This comparison is shown in Table 2-9 for 500 kW and 1500 kW units. It may have been anticipated that the profiles characterized by low values of the Weibull parameter k would result in lower costs, since these profiles have longer durations at higher wind speeds and therefore more energy available. However, this presumption would not have accounted for the effects of operation above rated speed. Between rated wind speed and cut-out velocity, the WTG operates so as to maintain rated power. This has the effect of truncating the energy produced at higher wind speeds. As can be seen in Table 2-9, systems designed for velocity duration profiles having a greater high velocity content optimized at rated speeds only slightly higher than those for the baseline designs, while cut-in speed also increased. The net result was a reduction in the total energy produced that was not offset by a reduced system cost. On the other hand, systems designed for velocity duration profiles having a greater low velocity content operated longer at rated power and produced more energy at higher cost. The optimum velocity duration profile, in terms of minimum energy generation costs, evidently lies between the two extremes considered.

Comparison of the capital investment costs ($/kW) shows that reduced cost results from assuming a velocity duration profile with more high velocity content. This is a result of the increased rated speed which allows a smaller rotor diameter. Rotor costs are a major element of the total system cost and are modeled in the computer program to increase as the rotor diameter to the exponent 2.22.

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TABLE 2-9

COMPARISON OF OPTIMIZED WTG DESIGNS

RATED POWER	500 kW			1500 kW		
	BASELINE DESIGN	WEIBULL PARAMETERS c = 6.05m/s, k = 1.6	WEIBULL PARAMETERS c = 6.05 m/s, k = 2.4	BASELINE DESIGN	WEIBULL PARAMETERS c = 9.1 m/s, k = 2.1	WEIBULL PARAMETERS c = 9.1 m/s, k = 2.1
ROTOR DIAMETER (m)	55.58	50.48	58.22	57.83	68.39	62.63
ANNUAL ENERGY (10^6 kWh)	1.88	1.56	1.95	6.61	6.12	7.15
RATED VELOCITY (m/s)	7.30	7.87	7.04	10.13	10.05	9.51
ENERGY GENERATION COST (¢/kWh)	3.10	3.32	3.18	1.32	1.44	1.34
CAPITAL INVESTMENT COST ($/kW)	712	628	760	354	358	388

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The comparison of capital investment costs with the baseline design costs is consistent for the 500 kW unit, but not for the 1500 kW unit. This is to be explained by the fact that the wind profile for the 1500 kW baseline design had a mean wind speed of 18.5 mph rather than 18 mph. When corrected for this factor, the results are more consistent.

2.3.2 BASELINE DESIGN WTG IN VARYING VELOCITY PROFILES

The effects of operating the baseline WTG systems in locations having the same mean wind speed but varying velocity duration profile, are shown in Tables 2-7 and 2-8 for the 500 kW and 1500 kW units, respectively. In all cases, the power generation costs increased when extremes in the velocity duration profile were considered. Increases ranged from 2 to 9% as the result of an off-optimum design. However, the costs were not significantly different from the costs that result when the WRG design is optimized for a particular velocity duration profile.

2.4 CONCLUSIONS

1. The velocity duration profile has a significant effect on determining the optimum WTG design parameters, and therefore is an important characteristic to be considered for a potential WTG installation site.

2. For a given mean wind speed, the minimum energy generation cost (¢/kWh) does not occur at either extreme in the velocity duration profile but for some distribution in between.

   For a given mean wind speed, the minimum capital investment cost ($/kW) occurs for a velocity duration profile having a greater high velocity content, or low values of the Weibull parameter k.

4. The velocity duration profile has a significant effect on the energy generation cost of a WTG when it is operated in a region having the same wind speed for which it was designed, but a different velocity duration profile.

2.5 REFERENCES

1. "Design Study of Wind Turbines 50 kW to 3000 kW for Electric Utility Applications, Analysis and Design", NASA CR 134935, February 1976.

SECTION 3

EFFECT OF CAPACITY FACTOR ON WTG DESIGN

3.1 INTRODUCTION

As part of the Wind Turbine Generator (WTG) design study, reported in Reference 1, optimized preliminary designs were identified for 500 kW and 1500 kW systems. In the optimization process used in that study, energy generation cost (¢/kWh) was used as the payoff function and capacity factor was treated as a dependent variable. However, more detailed analysis of the utility application has shown that capacity factor is an important consideration that can influence the value that a utility places on alternate power generation equipment. The objective of this task was to determine the effect of capacity factor on the design parameters of a WTG, thereby indicating the cost penalty that would be incurred in selecting a design having a greater capacity factor than the optimum.

The capacity factor, sometimes called plant factor, is the energy output of a generation device over a period of time (typically one year) divided by the energy which would have been produced if the device had operated at full rated power for the entire time. It is important to utilities as a measure of saleable product (kWh of energy), which must generate the revenue to pay all system costs.

The approach used was to repeat the optimization analysis for the 500 kW and 1500 kW systems using the same assumptions and computer program used in the design study, but with a constraint that fixed the values of capacity factor.

3.2 METHOD OF ANALYSIS

The analysis was conducted using the WTG-OPT computer program used in the

previous design study. With fixed values of capacity factor used as a constraint on the steepest-ascent optimization problem, the independent variables rated power, velocity ratio at rated power, and rotor speed were optimized using energy generation costs (¢/kWh) as the payoff function. Capacity factors of .3, .4, .5, and .6 were used as input.

Optimum designs were computed for 500 kW and 1500 kW systems, using velocity duration profiles with median wind speeds of 5.36 m/s (12 mph) and 8.05 m/s (18 mph), respectively. The resulting cost factors, energy generation cost (¢/kWh) and capital investment cost ($/kW) were plotted as a function of capacity factor and are shown in Figures 3-1 and 3-2. Other significant design parameters for all cases are summarized in Tables 3-1 and 3-2.

3.3 DISCUSSION OF RESULTS

As shown in Figures 3-1 and 3-2, an increase in capacity factor over the value that provides minimum energy generation costs can only be achieved at the expense of an increase in both energy generation cost and capital investment cost. Small increases have only a small effect. For example, a 10% increase in the capacity factor for the 500 kW system (from .43 to .47) causes only a 1% increase in energy generation costs (from 3.10 to 3.13 (¢/kWh) and a 10% increase in capital costs (from 713 to 785 $/kW). Beyond a capacity factor of .6, however, costs rise more rapidly. For the 1500 kW system, a 10% increase in capacity factor (from .50 to .55) increases energy generation costs 5% (from 1.32 to 1.38 ¢/kWh) and capital costs 13% (354 to 400 $/kW). Because the 500 kW system was assumed to operate with a 5.36 m/s (12 mph) median wind speed and the 1500 kW system with an 8.05 m/s (18 mph) median speed, the optimum values of capacity factor differ and a direct comparison between the two power levels cannot be made.

FIGURE 3-1

EFFECT OF CAPACITY FACTOR
ON
ENERGY GENERATION COST

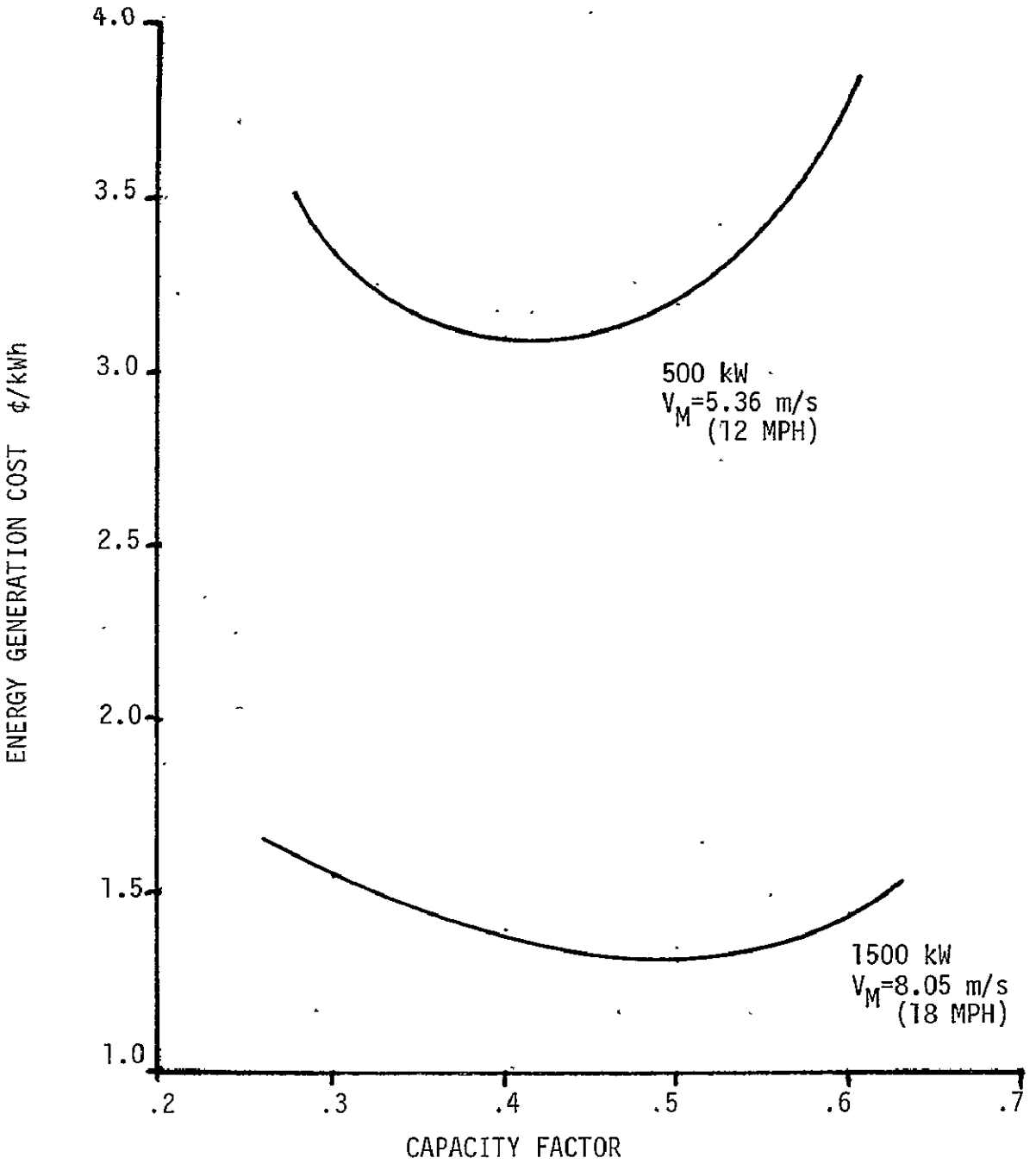

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FIGURE 3-2

EFFECT OF CAPACITY FACTOR
ON WTG CAPITAL COST

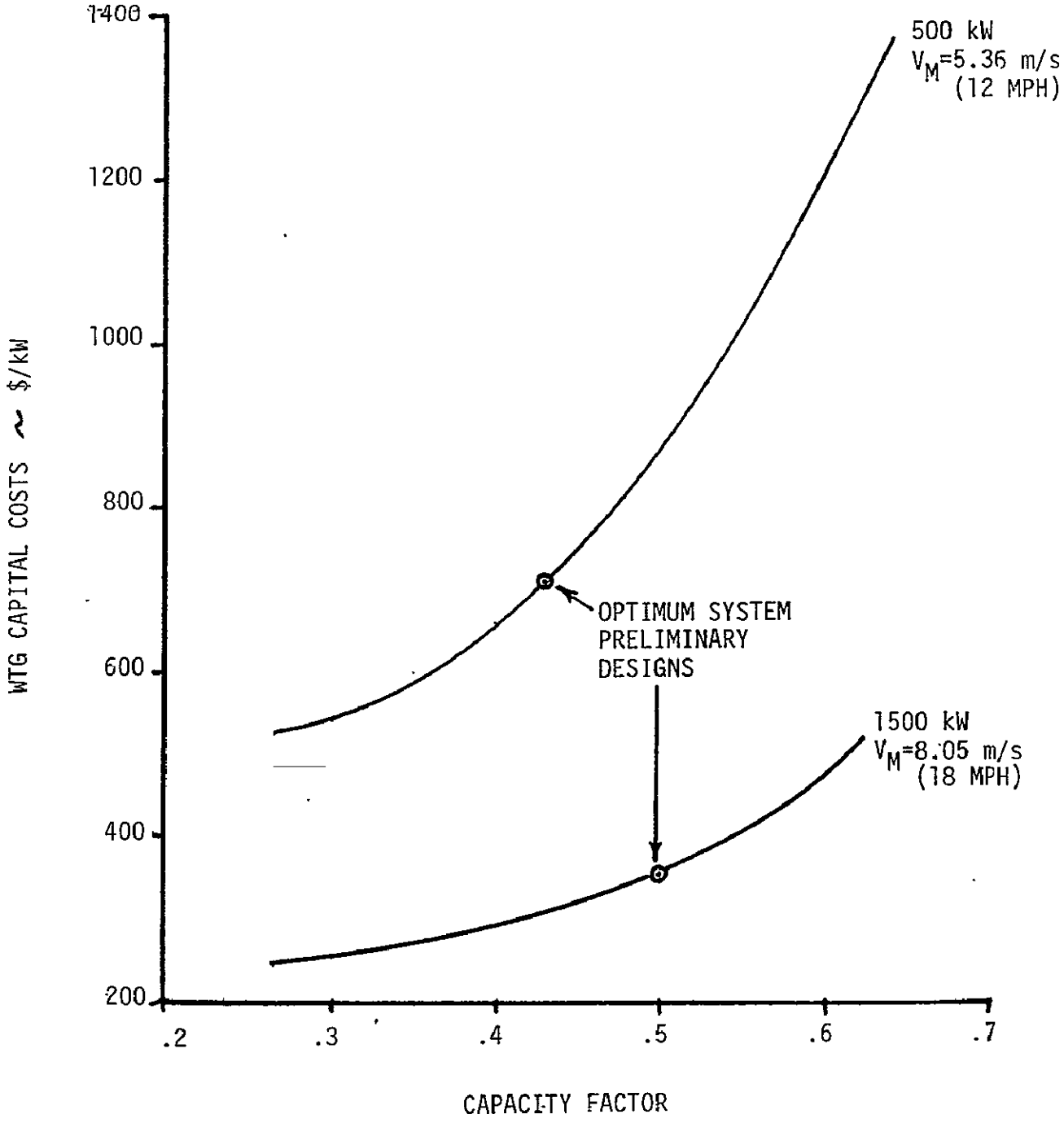

TABLE 3-1

EFFECT OF CAPACITY FACTOR ON DESIGN PARAMETERS FOR 500 kW SYSTEM

(MEDIAN WIND SPEED 5.36 m/s (12 MPH))

SYSTEM DESIGN PARAMETER	CAPACITY - FACTOR - CONSTRAINED SYSTEMS				OPTIMUM SYSTEM
CAPACITY FACTOR	.3	.4	.5	.6	.43
RATED ROTOR SPEED (rpm)	40.41	30.82	23.24	16.15	28.82
RATED VELOCITY (m/s)	8.77	7.62	6.59	5.48	7.30
ROTOR DIAMETER (m)	44.23	52.80	63.38	79.99	55.58
ANNUAL ENERGY OUTPUT (10^6 kWh)	1.33	1.76	2.18	2.61	1.88
ENERGY GENERATION COST (¢/kWh)	3.34	3.12	3.21	3.82	3.10
CAPITAL INVESTMENT COST ($/kW)	539	667	858	1231	713

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TABLE 3-2

EFFECT OF CAPACITY FACTOR ON DESIGN PARAMETERS FOR 1500 kW SYSTEM

(MEDIAN WIND SPEED 8.05 m/s (18 MPH))

SYSTEM DESIGN PARAMETER	CAPACITY - FACTOR - CONSTRAINED SYSTEMS				OPTIMUM SYSTEM
CAPACITY FACTOR	.3	.4	.5	.6	.503
RATED ROTOR SPEED (rpm)	67.29	53.80	40.67	28.29	40.77
RATED VELOCITY (m/s)	13.33	11.57	10.18	8.51	10.13
ROTOR DIAMETER (m)	40.93	48.74	57.50	72.28	57.82
ANNUAL ENERGY OUTPUT (10^6 kWh)	4.0	5.28	6.57	7.88	6.60
ENERGY GENERATION COST (¢/kWh)	1.57	1.38	1.32	1.46	1.32
CAPITAL INVESTMENT COST ($/kW)	251	293	352	472	354

The effect of imposing a capacity factor greater than optimum is shown in Tables 3-1 and 3-2 to be a reduction in rated velocity, which allows the WTG to operate for longer duration at rated power. As rated velocity decreases, rotor diameter increases, resulting in increased system cost. The rotor diameter has a strong influence on system costs because it is the single most costly element, and in the computer program its cost is modeled to increase with rotor diameter to the exponent 2.22.

3.4 CONCLUSIONS

1. Modest increases in capacity factor can be achieved with small increases in energy generation costs and capital costs.

2. Beyond a 10 to 20% increase in capacity factor, the cost penalty rises rapidly, primarily because of increased rotor costs.

3.5 REFERENCES

1. "Design Study of Wind Turbines 50 kW to 3000 kW for Electric Utility Applications, Analysis and Design", NASA CR 134935, February, 1976.

SECTION 4

CONCRETE TOWER DESIGN

4.1 INTRODUCTION

Esthetic appearance has been identified as a possible barrier to public acceptance of large wind turbine generator installations. This factor could be particularly important for potential sites in which there is high public visibility. During the preliminary design study performed under contract NAS 3-19403, an artist's concept was prepared to illustrate how an esthetic design might be achieved applying the technology of reinforced concrete structures to the WTG tower. The concept is illustrated in Figure 4-1. The objective of this task was to examine the concept in more detail, defining a preliminary design for which the cost could be estimated. By comparing the cost estimate with those for towers of more conventional construction, an assessment could be made of the cost penalty (if any), that might be imposed by esthetic considerations.

The approach used in this task was to prepare a preliminary design layout of a reinforced concrete tower, based on the earlier artist's concept. The design was developed using the same assumptions and design criteria used in the previous design study for a 1500 kW system. In particular, the stiffness of the tower was designed to provide a fundamental bending mode frequency 1.5 times the exciting frequency. The layout was prepared in sufficient detail to identify materials of construction, sizes and weights of major members and fabrication and assembly procedures, so that a detailed cost estimate could be made. In addition, the cost was estimated for a tower design in which the

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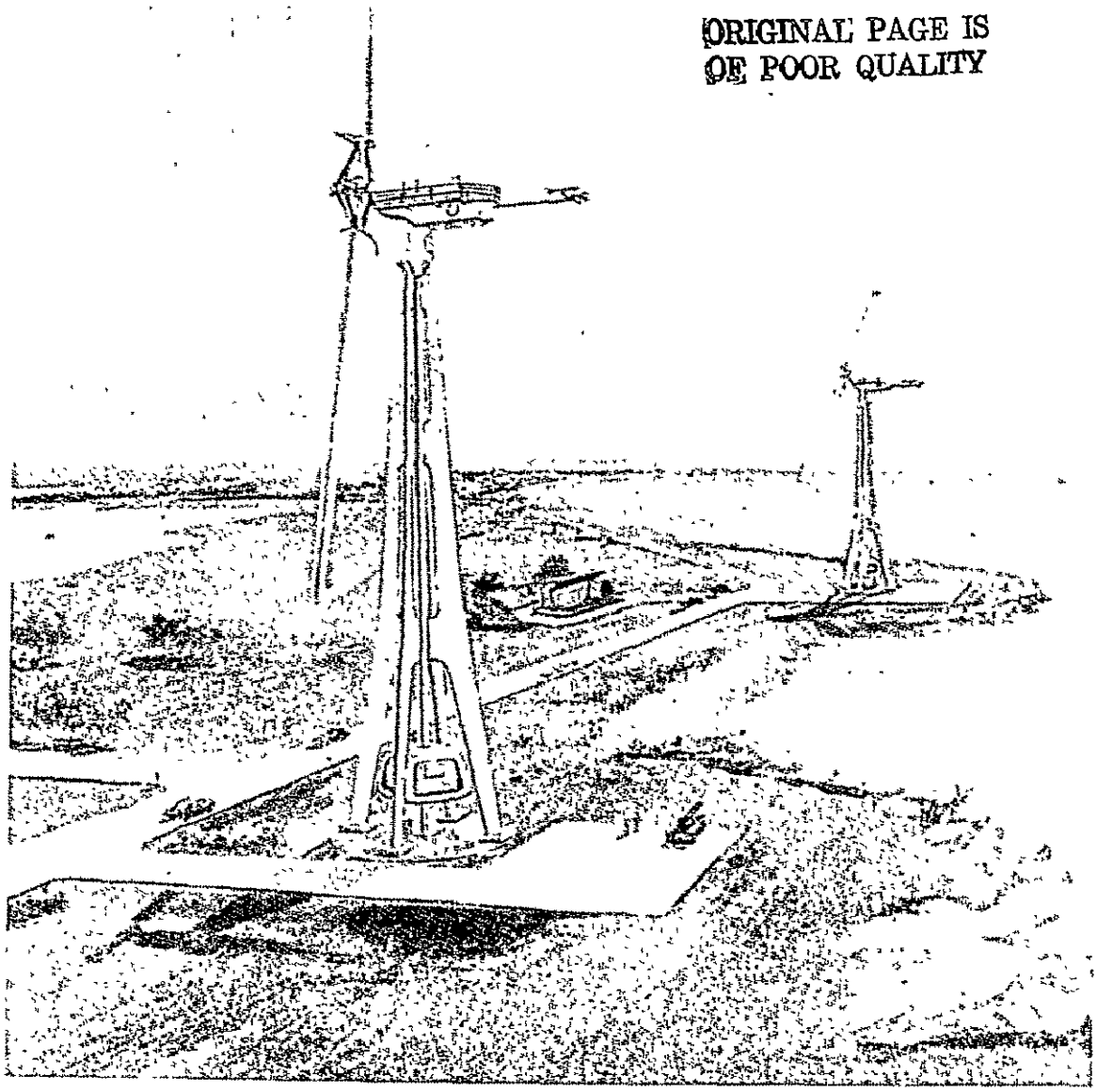

Figure 4-1. Artist's Conception of WTG
with Esthetic Concrete Tower

bending stiffness criterion was relaxed so that strength requirements governed. This corresponds to the limiting case for tower designs in which the natural frequency may be reduced to minimize dynamic load factors due to tower-rotor interactions.

4.2 METHOD OF ANALYSIS

Design and analysis of the tower was conducted by an iterative process, illustrated by the flow diagram in Figure 4-2. The first step was establishment of design requirements, based on the criteria and loading conditions used in the Design Study (Reference 1). These requirements are summarized in Table 4-1. The critical strength requirements for the tower were found to be those associated with a gust condition in which there is assumed to be an instant doubling of wind velocity while the system is operating at rated conditions. The maximum bending moment on the tower for this condition was found to be slightly greater than that resulting from the assumption of a 120 mph wind condition with blades stowed. The critical design loads are summarized in Table 4-2.

The next step was to establish appropriate strength criteria, applicable to reinforced concrete structures subjected to alternating loads. Conservative criteria were adopted, based on the recommendations of the American Concrete Institute (Reference 2). An exception to these recommendations was a further restriction of the allowable stress in the steel reinforcing rods due to

FIGURE 4-2

DESIGN AND ANALYSIS PROCEDURE

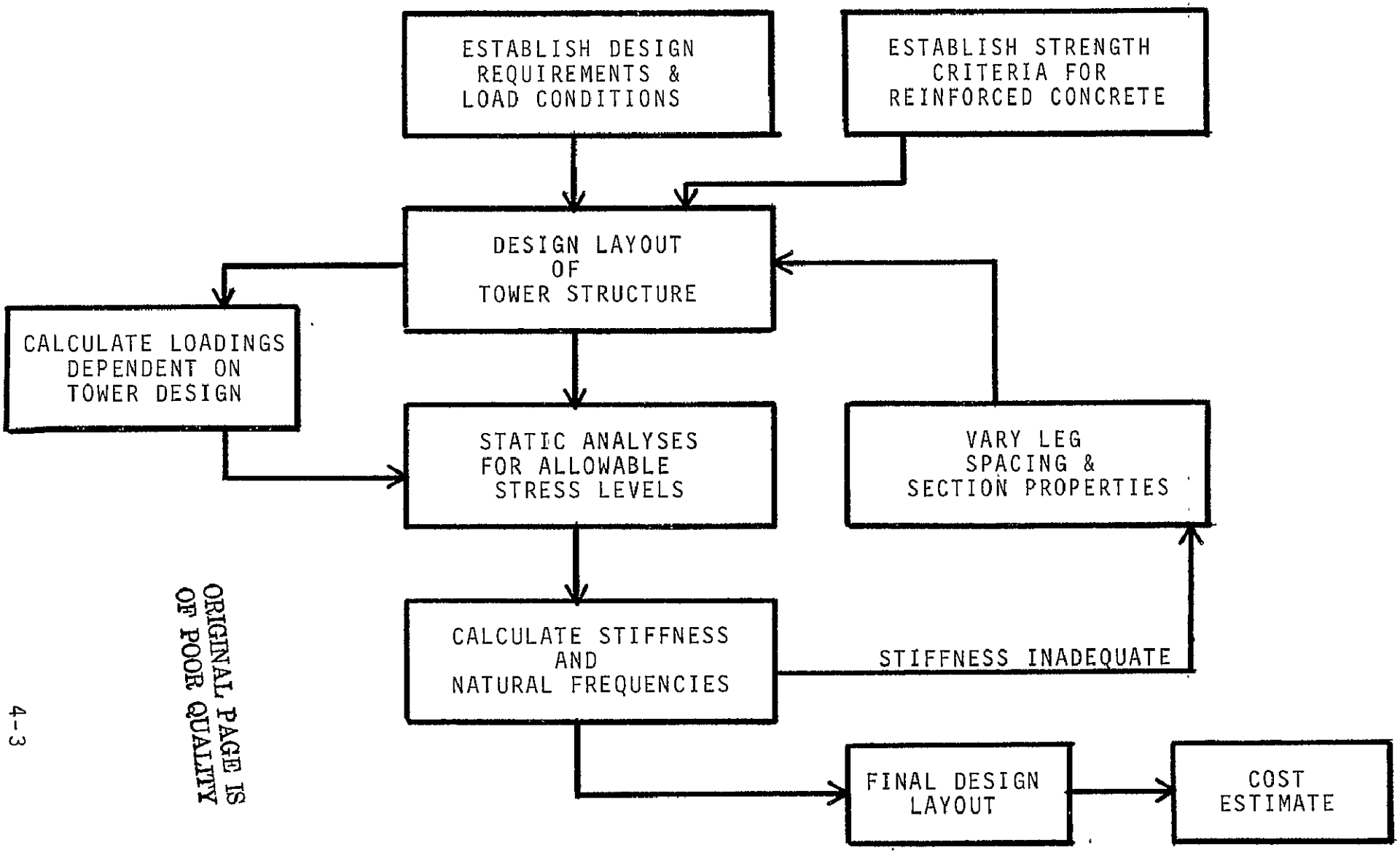

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TABLE 4-1

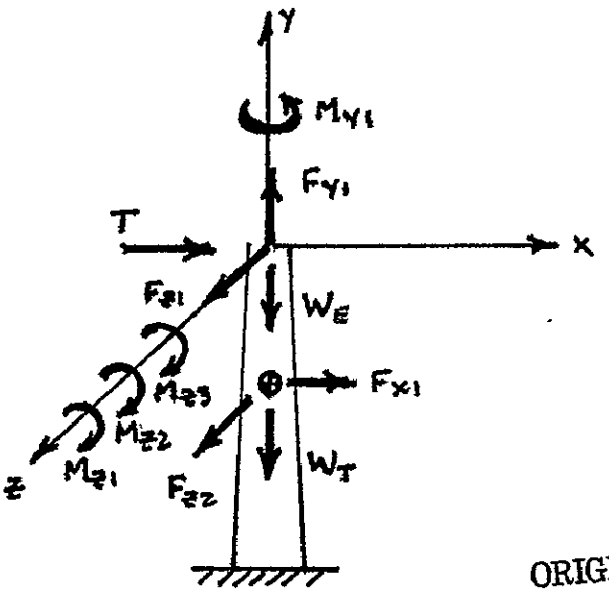
DESIGN REQUIREMENTS FOR CONCRETE TOWER

TOWER HEIGHT:	140 FT.
ROTOR RATED SPEED:	40 RPM
UPPER EQUIPMENT WEIGHT: (ROTOR AND NACELLE)	121,000 LB
RATED WIND SPEED:	22.5 MPH (10.1 m/s)
CUT-OUT VELOCITY:	50 MPH (22.3 m/s)
DESIGN LOAD CONDITION:	GUST, CAUSING INSTANTANEOUS DOUBLING OF WIND SPEED WHILE AT RATED CONDITIONS
MAXIMUM WIND LOAD CONDITON:	120 MPH WITH BLADES STOWED
DESIGN LOAD FACTOR:	1.35
FUNDAMENTAL BENDING MODE FREQUENCY:	1.5 TIMES EXCITING FREQUENCY
TORSIONAL MODE FREQUENCY:	AT LEAST 2.5 TIMES EXCITING FREQUENCY AND A NON-INTEGRAL MULTIPLE

TABLE 4-2

DESIGN LOADING CONDITION

(BASED ON GUST CAUSING AN INSTANTANEOUS DOUBLING OF RATED WIND SPEED)



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SYMBOL	TYPE LOAD	LOAD
T	THRUST	75 kips
M_{Z1}	MOMENT DUE TO THRUST COUPLE	600 ft-kips
F_{Z1}	SIDE LOAD	75 kips
M_{Y1}	MOMENT DUE TO SIDE LOAD	75 ft-kips
F_{Y1}	VERTICAL LOAD	75 kips
M_{Z2}	MOMENT DUE TO VERTICAL LOAD	75 ft-kips
F_{X1}	TOWER WIND LOADING	*
F_{Z2}	TOWER WIND LOADING	*
W_E	UPPER EQUIPMENT WEIGHT	121 kips
W_T	TOWER WEIGHT	*
M_{Z3}	GYRO MOMENT DUE TO YAW	134 ft-kips

* CALCULATED FOR EACH TOWER DESIGN

prestressing. By limiting the maximum stress to 0.2 times the yield stress, which is below the endurance limit for structural steels, an infinite fatigue life under alternating load was ensured. The strength criteria are summarized in Table 4-3.

As shown in Figure 4-2, the starting point in the iterative design process was to select a tower configuration with leg cross-sections and reinforcing rods that provided acceptable stress levels meeting the criteria established in Table 4-3. Following conventional analysis techniques for composite structures, the equivalent transformed section was calculated by converting the steel sections to equivalent concrete areas. Homogenous concrete section properties were then calculated and used to calculate maximum stresses under combined loads. Prestressing was assumed, sufficient to ensure no tension in the concrete. For each iteration of the design it was necessary to recalculate the loading conditions as they changed with tower weight and projected area in the wind.

The next step was to check the design for buckling of the legs between transverse supports and for shear stresses. Loading due to a 120 mph wind condition was checked to ensure that maximum bending moments on the tower remained less than those determined for the gust load condition.

The fundamental bending mode frequency was calculated by assuming a lumped mass on a uniform weightless cantilever beam, using the relation:

TABLE 4-3

STRENGTH CRITERIA FOR REINFORCED CONCRETE

ALLOWABLE CONCRETE COMPRESSIVE STRESS:	.40 f'_c
f'_c, 28 DAY COMPRESSIVE STRENGTH:	3750 psi
NO TENSION PERMITTED FOR REPEATED LOADS	
PRESTRESSING CABLE ULTIMATE TENSILE STRESS	250,000 psi
REINFORCING ROD YIELD STRESS:	40,000 psi
MAXIMUM COMPLETELY REVERSED STRESS IN REINFORCING RODS:	0.2 YIELD STRENGTH
SAFE BEARING CAPACITY OF FOUNDATION:	8000 LB/FT^2

$$\omega_{N1} = \left(\frac{3\ EI_{av}}{\ell^3\ m}\right)^{1/2}$$

where:

E = elastic modulus

I_{av} = average moment of inertia

ℓ = tower height

m = total weight

An estimate of the average moment of inertia was obtained by deriving an empirical relation of the form:

$$I(x) = A\ e^{bx}$$

where A and b were selected to fit values of I calculated at five vertical stations. The average moment of inertia was then defined as:

$$I_{av} = \frac{\int_0^{\ell} A\ e^{bx}\ dx}{\ell}$$

This method of calculating the natural frequency predicts a conservatively low value. For the final design selection, the frequency was checked using two alternate methods:

(a) The frequency of the tower alone as a uniform cantilever and the frequency of the lumped mass of the nacelle and rotor on a weightless cantilever were combined using Dunkerley's equation.

(b) The basic beam equation was solved:

$$EI\ \frac{d^2y}{dx^2} = -M$$

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using the empirical relation for I as a function of length. This method provides the most accurate estimate of bending frequency.

The tower natural frequency in torsion was calculated using the relation:

$$\omega_T = \left(\frac{GJ}{\ell I}\right)^{1/2}$$

where:

G = shear modulus

J = polar moment of inertia

I = mass moment of inertia

The polar moment of inertia was estimated by computing an average value:

$$J_{av} = \frac{\int_0^{\ell} J(x)\, dx}{\ell}$$

where $J(x) = A' e^{b'x}$, an empirical relation fitting values of J calculated at five stations. The mass moment of inertia was calculated by combining the moments of inertia of the rotor, nacelle, and tower.

If calculation of bending frequency showed that the tower stiffness was inadequate, the design was modified and the analysis was repeated. Stiffness was increased by increasing leg spacing and section properties as required. Design iterations were continued until both stiffness and strength criteria were satisfied.

The final step in the design process was to check the foundation loadings. Soil shear resistance was assumed to increase with

depth according to:

$$S_s = .50 + .00417d$$

and safe soil bearing capacity was assumed to be 8000 lb/ft^2. Spread footings were selected to be twice the diameter of piers to limit pier bending in accordance with conventional practice.

Having developed a tower design that met all requirements, a detailed preliminary design layout was completed with sections of important details. A detailed cost estimate was then prepared, based on the layout. The final tower design developed by this iterative procedure is described in the following paragraphs.

4.3 DESIGN DESCRIPTION

4.3.1 GENERAL DESCRIPTION.

The tower design is illustrated in Figure 4-3 with additional sections shown in Figure 4-4. Overall height is approximately 140 ft. and the envelope diameter tapers from approximately 44 ft. at ground level to 12 ft. at the pintle interface. The tower structure consists of four prestressed, reinforced concrete legs with transverse connections at four levels. The top connections also attach to a steel tank that serves as a load distributor and a protective housing for the yaw bearing and yaw drive mechanisms. The four legs are each composed of four sections, 35 ft. long having the same structural cross-section and differing only in the interconnecting structure and faired concrete gussets. Each leg section has the same camber so that the assembled tower has a uniformly curved taper that is esthetically attractive.

The basic structural section for each leg is a 2 ft by 4 ft rectangle of concrete with 24 steel reinforcing rods, distributed to place 16 rods in the outer half of the section and 8 in the inner half. The concrete is a lightweight structural grade with high strength and high modulus. The reinforcing rods are assumed to be a grade 40 (40,000 psi yield stress), deformed type, no. 8 size (1.0 in. diameter). In addition to the reinforcing rods, each section has 6 prestressing cables or "tendons", also distributed to place 2/3 in the outer half of the section. These cables

FOLDOUT FRAME 1

FOLDOUT FRAME 2

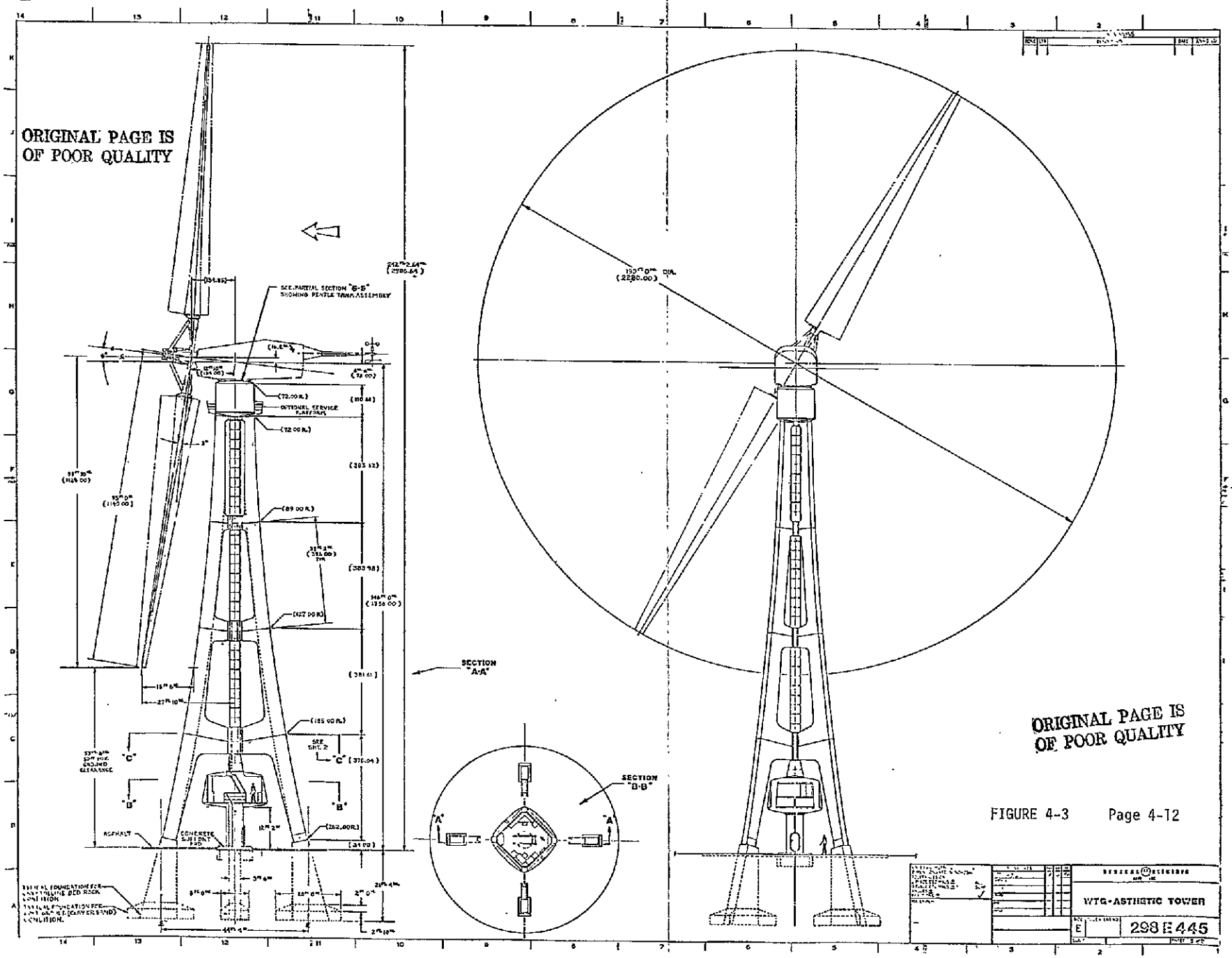

FIGURE 4-3 Page 4-12

are assumed to be 7-strand, high strength steel (250,000 psi ultimate tensile strength), attached to prestressing loading plates at the ends of each leg section.

The transverse connections between legs are prefabricated welded assemblies, composed of standard structural steel shapes, A36 grade (36,000 psi yield strength). Field joints are assembled using one inch diameter high strength steel bolts.

The tower foundations are conventional reinforced concrete piers with spread footings at a depth of 23 ft. In practice, the foundation would be designed according to the actual soil properties at the proposed site as determined from test borings and samples.

Other features of the tower design are an integral, prefabricated control building and a caged ladder providing access to the pintle and nacelle. The control building may house instrumentation, data recording equipment, remote control terminals, and similar equipment. Prefabricated units, similar to the design shown, are commercially available. Locating the building within the tower structure minimizes land use and the costs of additional site preparation.

A weight estimate of the tower is summarized in Table 4-4. The total weight, excluding the control building and foundation is 665,000 lb. This compares closely with the 650,000 lb that was estimated for a cylindrical concrete tower analyzed in the earlier design study (Reference 1, page 5-113).

TABLE 4-4

WEIGHT ESTIMATE FOR CONCRETE TOWER

	WEIGHT (LB)	
LEG SECTIONS, EACH	37650	
TOTAL FOR 16 LEG SECTIONS		602,400
CONNECTING STRUCTURAL STEEL ASSEMBLIES, EACH	12875	
TOTAL FOR 4 CONNECTIONS		51,500
PINTLE TANK		10,000
CAGED LADDER AND OTHER TOWER ACCESSORIES		1,100
TOTAL TOWER WEIGHT		665,000

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4.3.2 FABRICATION AND ERECTION PROCEDURE

The design concept was developed with the intention of minimizing the amount of field assembly time and labor, while keeping the section sizes small enough that they could be easily transported and handled. The sixteen leg sections that make up the tower structure are prefabricated assemblies that require only bolted connections in the field.

Fabrication of the leg sections would begin with construction of forms, which could be plywood, plywood plastic-lined, or steel depending on the total number of units for which the forms are intended to be used. The reinforcing framework would then be laid in and tack welded prior to pouring of the concrete. If a post-tensioning approach were to be used, the guyway filler cores would then be removed and the tendons installed when the concrete was sufficiently dried. The tendons would then be grouted in place and tendon end plates installed. Each of the six tendons would be prestressed to about 98,000 psi to account for relaxation losses, resulting in a total preload of approximately 525,000 lb or 400 psi. (For the design chosen, the quantity of steel is probably above the optimum,and some savings in cost may be possible by using fewer rods and greater tendon prestress).

The prefabricated leg sections are 35 ft. long and weigh approximately 38,000 lb each. This allows them to be shipped to the site without the need for special permits and without incurring a premium shipping rate. After the foundation had been prepared and cured, the first four leg sections could be erected using a

50 ton crane and secured to their footings. The cylindrical structure and mating structural assemblies would be erected and the four leg sections bolted together. The procedure would then be repeated for each level of the tower up to the pintle tank. Caged ladder assemblies, the control building, and other tower accessories would then be installed to complete assembly of the tower.

4.4 COST ESTIMATES

Cost estimates were prepared for the concrete tower, based on the final design shown in Figure 4-3. The major categories included in the cost were:

(a) Clearing and preparation of site.

(b) Foundation preparation

(c) Fabrication of parts and assemblies

(d) Assembly

(e) Control building andtower accessories.

Not included were the following:

(a) Land acquisition

(b) Site surveys

(c) Access roads

(d) Site power and utility services

(e) Site security (fencing)

(f) Engineering

The principal reference for cost estimates was the "Building Cost File, 1976 Eastern Edition", regionally adjusted to the Cleveland, Ohio area. The costs listed in this reference include performing contractors overhead and profit, and reflect the total cost to a prime system or general contractor. Detail work sheets for each of the major categories are included as Tables 4-5 through 4-9, and a cost summary for unit fabrication is shown in Table 4-10.

For quantities of 10, 100, and 1000, the unit cost estimates were modified to account for amortization of form costs, quantity discounts, and learning curve factors. For 10 or more units, steel forms were assumed at twice the cost of plywood forms, then amortized over the number of units. Factors of .95, .90, and .85 were assumed as discount and learning curve factors and applied to the fabrication and assembly costs for quantities of 10, 100 and 1000, respectively. The results were as follows:

1 unit	$137,000
10 units	127,000
100 units	123,000
1000 units	119,000

These cost estimates are considerably higher than the comparable costs for a cylindrical concrete tower estimated in the previous design study ($55,900 to $64,000), but are close to those estimated for a steel truss tower ($98,100 to $122,400).

TABLE 4-5

A. CLEAR AND PREPARE SITE

- DEMOLITION
- EARTHWORK
- ASSUME 1 ACRE SITE FOR WTG INSTALLATION

COST ITEM	UNIT	MAT'LS	LABOR	EQUIP.	TOTAL
• SELECTIVE THINNING OF MEDIUM DENSE AREAS P. 3-0210212	ACRE-X1	-	333	369	702
• STUMP REMOVAL AND HAUL OUT BY MACHINE (14" TO 18" DIAM.) P. 3-0210508	EACH-X5	-	23-115	20-100	215
• POROUS CONCRETE PIPE (6") FOUNDATION UNDERDRAIN P. 6-0220815	L.F. X 100'	.74- 74	2.54-254	-	328
• ROUGH GRADING AND LEVELING W/PATROL GRADER P. 8-0221503	S.Y.-X4833	-	.06-290	.13-628	918
					$2163
			REGIONAL ADJUSTMENT: X0.853		$1845

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B. FOUNDATION PREPARATION

COST ITEM	UNIT	MAT'LS	LABOR	EQUIP.	TOTAL
• MOBILIZATION AND DEMOBILIZATION OF EQUIPMENT (Avg. $1) P.13-0230101	EACH-X1	-	924	1647	2571
• BELL BOHOM EXCAVATING & CONCRETING (WET;2500 psi) P.-18-0235502	C.Y .-4X12.5	87-4350	122-6100	35-1750	12200
• REBARS FOR PILES (CAISSONS) P.-18-0235701	#-X4000	.17-680	.26-1040	-	1720
• CAISSON CAPS (320 TON) P. 18-0235803	EACH-X4	379-1516	308-1232	-	2748
• PURCHASE,PLACE, LEVEL, COMPACT CRUSHED STONE (44 FT^2, 6" THICK)	C.Y.-X28	5.77-161	6.34-177	3.37-94	432
					$19671
			REGIONAL ADJUSTMENT: X.853		$16779

TABLE 4-7

C. FABRICATION OF PARTS AND ASSEMBLIES

- 280 ft^3/leg x 16 legs = 4480 ft^3 166 yd^3 concrete
- faired concrete structure for esthetics = 20 $yd.^3$
- rerods 2800 lb/leg; 45000 lb./tower
- tendons 820 lb/leg; 13120 lb/tower
- leg connecting structure: @ 0', 7700 lb @ 35 ' 11000 lb @ 70' 14400 lb @ 105' 18400 lb Total 51500 lb
- pintle "tank" 10000 lb

(p. 48 - Note instructions - precast structural concrete)

COST ITEM	UNIT	MAT'LS	LABOR	EQUIP.	TOTAL
• PLYFORMS FOR BEAMS - ASSUME TYPICAL 5 USES. P. 35-0310303	ft^2	0.31	1.30		
- 1st BAY	420	$130	$546		
- 2nd BAY	462	$143	$601		
- 3rd BAY	504	$156	$655		
- 4th BAY	504	$169	$710		
0310523: FOR LONG, RADIAL FORM CONSTRUCTION ADD 16% TO TOTAL COST					3608
• PLACE REINFORCEMENT P. 43-0321605	TON X 22.5	656-14760	263-5918	42-945	24866
	(11 TO 49 TON JOB ADD 15% TO TOTAL COSTS)				
0321614 - 10, 100, 1000 TOWERS DEDUCT 5% TOTAL COSTS					
• CAST IN PLACE 4000 psi LIGHTWEIGHT STRUCTURAL CONCRETE P. 46-0332203	C.Y. -x 186	45-8370	18-3350	-	11720
• PRESTRESSING, STEEL, 50 ft. SPAN, 300 kip GROUTED "MEANS" P. 48	lb.-x13120	TOTAL @ $1.50/LB.			19680
• LEG. CONNECTING STRUCTURE A 36 15000 LB = WELDMENTS 36,500 LB = CUT STANDARD SHAPES		TOTAL = 15,000 X 1.50/LB + 36,500 X $.75/LB			$49875
• PINTLE "TANK" 10,000 LB WELDMENT		TOTAL = 10,000 LB X 1.40/LB			$15000
					$124929
		REGIONAL ADJUSTEMENT: X.80 (.80 = COMPOSITE FOR PRECAST STRUCTURAL CONCRETE AND STRUCTURAL STEEL)			$99943

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TABLE 4-8

D. ASSEMBLY

COST ITEM	UNIT	MAT'LS	LABOR	EQUIP.	TOTAL
• MOBILIZATION & DEMOB. OF EQUIPMENT (AVG.) P. 13-0230101	EACH-X1	-	924	1647	2571
• 200' BOOM CRANE I&SE INPUT - EACH BAY 1 DAY TO COMPLETE	DAY-X1	$1500/DAY X 4 DAYS = $6000			6000
• ANCHOR BOLTS - 1.5" x 36" @ 16/TOWER MEANS P. 59- INC. NUT, WASHER, TEMPLATE	EACH X 16	7.75-124	14.40-230		354
• ASSUME (WITH CRANE) 7 MAN CREW (3 RIGGERS, 3 STEAMFITTERS, 1 FOREMAN) @ 5 DAYS @ $15/HR.		7 X 40 X 15			4200
• ASSUME MISCELLANEOUS TIE BOLTS AND STEEL STRUCTURE @ 1500 LB.		1500 LB X $1.50/LB			2250
					$15375
		REGIONAL ADJUSTMENT: X.932			$14330

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E. CONTROL BUILDING AND TOWER ACCESSORIES

COST ITEM	UNIT	MAT'LS	LABOR	EQUIP.	TOTAL
• CONTROL BLDG. FOUNDATION SLAB 10' X 10' X 6" P.-45-031108	C.Y.-X1.852	40.56-75	12.77-24	-	99
• RIGID FRAME PRE-FAB STEEL BLDG. 100 FT^2	S.F.-X100	3.82-382	1.10-110	-	
	(ADD 88% TO TOTAL COSTS FOR INSULATION AND ENAMEL FINISH)				925
• CAGED LADDER - AS PER BETHLEHEM STEEL 1975 @ $25/FT. ASSUME 1976 - 1.075 X $25/FT	140 FT X 1.075 X 25				3763
					$4787
			REGIONAL ADJUSTMENT:	X.932	$4461

TABLE 4-10

UNIT COST ESTIMATE SUMMARY

CLEARING AND PREPARATION OF SITE	1845
FOUNDATION PREPARATON	16779
FABRICATION OF PARTS AND ASSEMBLIES	99943
ASSEMBLY	14430
CONTROL BUILDING AND TOWER ACCESSORIES	4461
	$137,458

A further question of interest is how the concrete tower cost might be reduced if strength criteria governed rather than stiffness. This case is of interest because it represents the limiting case for tower designs that are optimized to minimize the dynamic loads from tower-rotor interactions rather than designing to avoid multiples of the exciting frequency. Leg sections designed only for strength could be reduced to 3.37 ft. by 1.685 ft. and still maintain stresses less than the 1500 psi allowable. This would result in a reduction in total tower weight of 171,000 lb ,and an estimated fundamental bending frequency of 1.72 cps, or 1.29 times the exciting frequency. The cost of concrete forms would be reduced by a factor of .845, and assuming that steel can be reduced in proportion to the concrete, all material related costs could be reduced by the factor .71. Total unit tower cost would then be $109,000, a reduction of 21%.

4.5 CONCLUSIONS

1. It is feasible to design reinforced concrete towers for wind turbine generator installations that are esthetically attractive while meeting stiffness and strength requirements.

2. The costs of such towers are higher than those for cylindrical reinforced concrete construction of more conventional design, but comparable with the costs of steel truss towers.

3. Concrete towers can be reduced in cost when produced in quantity, as much as 13% for a quantity of 1000.

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4. Design of a concrete tower to strength requirements rather than to an arbitrary stiffness can result in a cost reduction of 20% or more.

5. Note that the effects of tower "shadowing" or blocking some portion of the wind to the rotor have not been considered. A concrete tower may present significantly higher blockage than, for example, an open truss tower. This may have a major effect on rotor dynamics.

4.6 REFERENCES

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